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THE TWO-BODY ABRASION RESISTANCE OF STEELS CONTAINING LOW AMOUNTS OF CHROMIUM AND MOLYBDENUM

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SUMMARY

Two-body high-stress abrasion tests were carried out on chromium steels and chomium-molybdenum steels using flint and silicon carbide abrasive papers. Both types of steels were tested in three conditions of heat treatment: "as-received", hardened and tempered at 550°C, and hardened and tempered at 180°C. The results were compared with plain carbon steels similarly heat-treated. The effect of the steel hardness, the carbon content, the microstructure, the chromium-to-carbon ratio as well as the hardness of the abrasive were considered. The wear resistance of the alloy steels were found mostly within the range of the carbon steels, although the influence of the steel hardness varies greatly with the heat treatment of the steels and the nature of the abrasive particles. For a given heat treatment, the chromium steels usually exhibit a better relative resistance when the carbon content is low while the opposite is true with the chromium-molybdenum steels.

1. INTRODUCTION

The development of new abrasion resistant materials contributes to lower the economic losses due to wear. A good comprehension of wear mechanisms is however necessary to achieve their elaboration. Although basic principles governing the abrasion of materials are well understood so that some general rules have been formulated, these are still rather empirical and each case of deterioration by wear remains specific to a particular tribosystem. More experiments are thus needed, which could help to reduce wear losses by increasing the existing knowledge on the wear behaviour of common materials, as well as through the development of new materials.

Early works showed that the wear resistance of a material could be related to its bulk hardness [1,2] but that this latter parameter could not be used as the only indicator of resistance to abrasion since materials of equivalent hardness but of different types often exhibited different wear resistance values. The abrasion resistance is also dependent on the ratio of the hardness of the abrasive to that of the material being worn. A low hardness ratio is associated with a low level of wear while a high ratio leads to a high level. The two levels are linked by a region where the abrasion resistance is more sensitive to this parameter [3].

The microstructure of tested materials is a variable of importance, especially the presence of a second phase, its nature, amount, hardness, size and shape [4]. Plain carbon steels were among the first two-phase materials to be investigated from the point of view of the influence of microstructure on the wear resistance. An increase in carbon content of hypoeutectoid plain carbon steels leads to an increase of hardness and of abrasion resistance [5]. For a given hardness, a steel having a higher carbon content is usually more wear resistant [6]. The microstructures of carbon steels can be ranked roughly from the least to the most wear resistant as follows: tempered martensite, pearlite, martensite, bainite [7]. Such a ranking is however subject to modification when particular materials are tested. Since the wear behaviour of carbon steels is now quite well known, they are often used as a

reference to evaluate and understand that of more complex materials.

In contrast to what can be found in the literature about the wear properties of plain carbon steels, little information is available on steels with a small amount of chromium and molybdenum. Although many studies were conducted on the wear resistance of high chromium cast irons, none of their results are directly applicable to steels, mainly because of differences in the nature and the quantity of carbides. Two-body high-stress wear resistance experiments were then carried out on chromium steels (approx. 1% Cr) and chromium-molybdenum steels (approx. 1% Cr and 0.2% Mo) submitted to heat-treatments such as normalizing, hardening and tempering. The values of resistance to wear by flint and silicon carbide abrasives were compared with those of plain carbon steels similarly heat treated, as related to bulk hardness, carbon and alloying element contents and microstructure.

2. EXPERIMENTAL METHOD

2.1 Materials

2.1.1 Chemical Composition

Two groups of alloy steels were investigated. Their compositions are given in Table I. The first group is formed by three chromium steels: 28Cr4, 34Cr4 (AISI 5132) and 41Cr4 (AISI 5140). The second group is composed of five chromium-molybdenum steels: 16CrMo4, 25CrMo4, 34CrMo4 (AISI 4137), 42CrMo4 (AISI 4140), and 50CrMo4. It is important to note that with these steels, the real influence of molybdenum alone cannot be distinguished and directly compared with that of chromium in the former group. Rather, the combined effect of chromium and molybdenum must be considered.

The composition of each hypoeutetoid plain carbon steel used as reference is also included in Table I.

2.1.2 Heat treatments, microstructures and hardness

Each group of steels was tested in three conditions of heat treatment. Details are given below and summarized in Tables II, III and IV, together with the resulting hardness values and microstructures.

The normalized condition was the as-received condition of most of the materials. Ferrite and pearlite are the microstructure constituents of the plain carbon steels and chromium steels. Bainite and martensite are also present to different extents in the as-received steels 34CrMo4 (AISI 4137), 42CrMo4 (AISI 4140), and 50CrMo4. All steels were also hardened and tempered at two different temperatures. Tempered martensite was obtained after a hardening and a tempering at 550°C for one hour. After a similar heat treatment at 180°C (for 60 or 90 minutes) the tetragonal martensite decomposes into ε-carbides and cubic martensite while the structure of the retained austenite remains unchanged. The steels 16CrMo4 and 25CrMo4 were also hardened and tempered at 550°C and 180°C, but they were quenched into oil instead of water and the resulting slower cooling rate allowed the formation of bainite.

Figures 1 to 3 show the relation between hardness and carbon content of the steels for all compositions and heat treatments. The addition of chromium increases the hardness of normalized steels and of steels tempered at 550°C, as compared to plain carbon steels. The molybdenum further increases the hardness. The influence of chromium and molybdenum changes when the steels are tempered at 180°C. While both elements have no effect on the hardness of steels having more than 0,4% C, they slightly soften those containing less carbon. It is also to be noted that both the chromium steels and the chromium-molybdenum steels follow the same linear regression.

2.2 Abrasion tests

2.2.1 Description of the test method

The abrasion test rig, shown in Figure 4, is a "turn-table" type apparatus normally used for polishing purpose. One of its main characteristics is that the sample passes several times on the same abrasive particles. The rotation speed (n_1) of the abrasive paper is 125 min^{-1} while that of the sample support (n_2) is 3 min^{-1} with respect to the eccentric axis. The annular shaped sample (42 mm O.D., 16 mm I.D.) is free to rotate on its own symmetry axis. Both flint and silicon carbide are used for the tests. The nominal grit diameter is 70 µm (paper grade 220) and the applied pressure is 0,019 N/mm^2. The test duration is 3 minutes per measurement and the wear resistance of each steel is the mean of usually four measurements on a unique specimen.

The wear rate of a sample should usually be expressed by its volume loss because it permits direct comparison of materials having different specific gravities. Since the differences in specific gravity of the investigated steels are not large enough to result in misleading wear values, the weight loss was preferred for expressing them, because a more accurate measurement was easier to perform.

2.2.2 Correction for paper abrasiveness

Flint abrasive discs of a single batch were used to perform the tests and the abrasiveness is therefore approximately constant. On the other hand, two different batches of silicon carbide papers were used. A correction method to compensate for their different abrasiveness was established as follows.

Tests were carried out with both batches of silicon carbide abrasive paper on seven selected normalized samples. Figure 5 illustrates the correlation between the two sets of results. It is seen that the regression line intercepts the ideal situation of equal weight losses at a value of 110

mg. Since the weight loss ratio varies with the wear resistance value, the corrected weight losses were calculated by using the regression line appearing in Figure 5 instead of a constant mean ratio. For weight losses lower than 110 mg, no correction was made because it could be assumed that both batches have a comparable abrasiveness.

The correction equations were therefore the following:

$$\Delta W_{SiC_I} = 1{,}4637 * \Delta W_{SiC_{II}} - 51{,}72 \qquad \text{if } \Delta W_{SiC_{II}} > 110 \text{ mg} \qquad (1)$$

$$\Delta W_{SiC_I} = \Delta W_{SiC_{II}} \qquad \text{if } \Delta W_{SiC_{II}} \leqslant 110 \text{ mg} \qquad (2)$$

where the mass losses are expressed in mg. The coefficient of correlation of Equation (1) was evaluated at 0,99.

2.2.3 Relative wear resistance

The effect of alloying elements forming different types of carbide can be due partly to their influence on the bulk hardness but also to the interaction between individual carbides and abrasive particles. One question is what proportion of the total effect can be attributed to each of these causes. In order to eliminate the effect of undesired variations of the test conditions, the wear resistance is often presented in the form of a relative value expressed as the ratio of the weight loss of a standard specimen to that of the investigated material, both tested under the same overall conditions. In this calculation, the replacement of the wear resistance of a standard specimen by a standard relation between wear resistance and hardness should help to distinguish the role to be attributed to the individual "carbide-abrasive particle" interactions.

Though the cementite of hypoeutectoid plain carbon steels is much harder than ferrite, its presence in softer pearlite or as small particles greatly

reduces its capability to resist the action of an abrasive particle. The wear mechanisms will not vary significantly with the carbon content and, to a first approximation, the increase of wear resistance with increasing carbon may be attributed to the effect of hardness [8]. Consequently, the relation between their absolute wear resistance (the inverse of their weight loss in grams) and the hardness (HV10) has been considered as the "standard value". The relative wear resistance of an alloy steel was then expressed as the ratio of its own absolute wear resistance to that of a plain carbon steel of equal hardness, both tested after the same heat treatment and under the same conditions. The linear regression equations for the wear resistance of plain carbon steels have been used for the calculations. For example, if the relation $W^{-1} = m_1 H + b_1$ is found for the carbon steels after a given heat treatment and if an alloy steel, after the same heat treatment, has a Vickers hardness H_a and a wear resistance W_a^{-1}, its relative wear resistance value will be:

$$(R.W.R.)_a = \frac{W_a^{-1}}{m_1 H_a + b_1} \qquad (3)$$

A relative wear resistance value close to unity signifies that the change in wear resistance is mainly due to a hardness effect similar to that involved in the plain carbon steels, while the action of individual hard phases will lead to higher or lower values.

3. RESULTS AND DISCUSSION

3.1 Carbon steels

Since the tests on carbon steels were made essentially to serve as a reference for the alloy steels, the results are not fully discussed here. They can be found in a previous report [9]. In order to facilitate the comparison with the alloy steels, straight lines calculated by the method of linear regression are plotted in broken lines on Fig. 6 to 11. Calculated coefficients of regression are listed in Table V. As expected, linear

equations describe the dependence of wear resistance on bulk hardness or carbon content as well. The slope values indicate that the improvement of wear resistance with increasing hardness is smaller at low values of hardness. Hence, the series of harder steels constitute the transition from the level of low wear resistance to a constant high level, which is actually not observed in these tests.

It can also be pointed out that the hardening and tempering at 550°C lead to higher bulk hardness than normalized steels (Tables II and III) but not necessarily to higher wear resistance, which is in accordance with earlier results [5].

3.2 Chromium steels

No correlation is found between the wear resistance to flint of the normalized chromium steels and the hardness or the carbon content (Fig. 6). On the other hand, a strong relation exists when silicon carbide is the abrasive medium (Fig. 7). From a general point of view, the wear resistance of these steels is not improved when compared to plain carbon steels of equivalent hardness, but they exhibit higher values on the basis of carbon content. The only exception is the alloy 41Cr4 which has a wear resistance to silicon carbide substantially higher than the carbon steel of equivalent carbon content.

The addition of chromium to plain carbon steels shifts the pearlite point to a lower carbon concentration. In the normalized condition, the increased proportion of pearlite, as compared to plain carbon steels of equivalent carbon content, leads to a higher bulk hardness. The composition and the properties of the pearlite must be specific to each alloy since they should be influenced by the chromium content and the ratio of chromium to carbon. This is perhaps responsible for the lack of correlation between the wear resistance to flint and the bulk hardness or the carbon content. This is not so when the harder silicon carbide is used as abrasive since it can cut the hard phase of the steels, the differences in the microstructures becoming a less important

parameter.

The hardening and tempering of chromium steels at 550°C lead to a different wear behaviour. The wear resistance decreases with hardness or carbon content independently whether flint or silicon carbide is used as abrasive (Figs 8 and 9). These chromium steels are more wear resistant than the plain carbon steels, the difference becoming less as the bulk hardness (or carbon content) increases or when the softer abrasive is used. The resistance of the steel 41Cr4 abraded by flint is even lower than that of the plain carbon steel of equal hardness. These obervations are reflected by the values of relative wear resistance.

Relatively small quantities of carbides are formed in the lower carbon steels and the addition of chromium may modify their properties in such a way to greatly improve the wear resistance. Since the amount of chromium remains approximately constant, the carbides formed in steels having a higher carbon content include a lower proportion of chromium. Thus, their properties move toward those of plain carbon steels, and so does the wear resistance.

The chromium steels hardened and tempered at 180°C exhibit a better resistance to wear by flint than the plain carbon steels of equivalent hardness (Fig. 10) or carbon content. An increase of the amount of carbon leads to a higher hardness but to a lower wear resistance, closer to that of plain carbon steels, which may be attributed to the lower Cr/C ratio. When the abrasive is silicon carbide, the three chromium steels have equal wear resistance values (Fig. 11), within the range of the carbon steels.

Another representation of the effect of chromium is given in Figure 12 where the relative wear resistance is plotted against the chromium-to-carbon atomic ratio. Except for the normalized steels abraded by silicon carbide, an increase of the Cr/C ratio induces an improvement of the relative wear resistance. Thus, an increase of the Cr/C ratio leads to carbides which better resist the action of the abrasive particles. This improvement of wear resistance will be greater against relatively soft abrasive.

The inverse relation observed for the normalized chromium steels abraded by silicon carbide has to be clarified. Such inversions of the influence of a hard phase on the wear resistance were previously found in other tribosystems. It has been shown [3] that an increase of the amount of M_7C_3 carbides in martensitic CrMo white cast irons improves the resistance to abrasion by flint or alumina but has a negative effect against silicon carbide due to spalling. The higher Cr/C ratio of the normalized 28Cr4 steel may be responsible for a harder pearlite which better resists the action of flint, but which is also more easily cut by the silicon carbide. The relatively low amount of pearlite also enhances this phenomenon since the abrasive can penetrate deeper into the ferrite and be more capable of breaking the lamellar carbide.

3.3 Chromium-molybdenum steels

Wear tests on as-received chromium-molybdenum steels were carried out on only three alloys, namely the 34CrMo4, 42CrMo4 and 50CrMo4. The effect of hardness on the wear resistance is similar to that of plain carbon steels but the values are lower than expected from their hardness (Figs 6 and 7). When one considers the carbon content, both types of steels have comparable wear resistance values, except the steel 42CrMo4 abraded by silicon carbide which exhibits a much higher value.

The microstructures of these steels are complex mixtures of up to four different phases in different proportions (Table II). Thus, a clear explanation remains difficult to offer. We may however mention that the presence of martensite in the alloys 42CrMo4 and 50CrMo4 probably contributes to a better wear resistance, while the ferrite in the latter may be responsible for its relatively lower performance despite its higher bulk hardness.

An increase in hardness or carbon content of chromium-molybdenum steels, hardened and tempered at 550°C, strongly improves the wear resistance (Figs 8 and 9). This influence is much more important than in the plain carbon

steels. The anomaly shown by the alloys 16CrMo4 and 25CrMo4 can be attributed to the ambiguous hardness values (see Fig. 2). The situation is rectified if the carbon content is used as independent variable (Figs 8b and 9b).

Two different microstructures are present in the Cr-Mo steels hardened and tempered at 550°C (Table III): bainite in the two low-carbon steels (16CrMo4 and 25CrMo4) and tempered martensite in the other three. This difference of microstructure has no real effect on the wear resistance which rather is related to the hardness (or more strictly to the carbon content). For low-carbon steels, the addition of chromium and molybdenum probably leads to the formation of a hard phase with a high (Cr + Mo)/C ratio, but it seems that when present in small quantity, this phase cannot resist the action of individual abrasive particles. Consequently, the wear resistance to flint does not really improve by comparison to plain carbon steels with equivalent carbon content. For abrasion by silicon carbide, the increase of hardness due to the alloying elements is not sufficient to compensate the poorer resistance of these carbides and the relative wear resistance values are in most cases lower than unity. Keeping the amount of chromium and molybdenum constant and adding carbon increase the amount of hard phase leading to a higher protection of the matrix and to an improved wear resistance against both abrasives in spite of the lower (Cr + Mo)/C ratio.

The wear resistance of the chromium-molybdenum steels, hardened and tempered at 180°C, lies on two levels (Figs 10 and 11). The two low-carbon alloy steels (16CrMo4 and 25CrMo4) exhibit equal values of wear resistance within the range of the plain carbon steels. This observation holds for wear by both abrasives. The other three steels (34CrMo4, 42CrMo4 and 50CrMo4) show a strong improvement of wear resistance. With flint as abrasive medium, the values are even higher than those obtained with the chromium steels. They seem however not to be related to the bulk hardness. A similar behaviour is noted for the abrasion by silicon carbide except that the high value of wear resistance is constant for the three alloys. The presence of bainite in these two steels may be responsible for the lower wear resistance, contrary to what was observed for the same steels tempered at 550°C.

4. CONCLUSIONS

4.1 Chromium steels

Heat treatable steels containing 1% chromium usually show a better wear resistance than plain carbon steels with equal carbon content. At equivalent hardness, these chromium steels may exhibit a higher or a lower wear resistance than the plain carbon steels, depending on the tribosystem.

Under most test conditions, a decreasing wear resistance is observed with increasing hardness (or carbon content) of the chromium steels.

Except for the case of normalized chromium steels abraded by silicon carbide, an increase of the Cr/C atomic ratio induces an increase of the relative wear resistance. The latter was defined as the wear resistance of an alloy steel divided by that of the plain carbon steel of equal hardness and abraded under the same experimental conditions. The lower Cr/C ratio of steel containing higher carbon could therefore explain their lower wear resistance.

4.2 Chromium-molybdenum steels

The wear resistance of normalized heat treatable steels containing chromium (from 0,96% to 1,17%) and molybdenum (about 0,20%) increases with bulk hardness or carbon content. The relative wear resistance values are lower than unity and not dependent on the Cr/C ratio. This behaviour may be attributed to differences in microstructure.

Hardness (or carbon content) influences the wear performance more strongly in the Cr-Mo steels hardened and tempered at 550°C than in carbon steels after the same heat treatment, but the effect is similar. The relative wear resistance values are lower than unity for the low-carbon alloy steels and become higher as the hardness increases. An increase of the Cr/C ratio lowers the relative wear resistance but coincides with a decrease of the carbon content which may also be the explanation.

The presence of bainite after a hardening and a tempering at 180°C of chromium-molybdenum steels containing low carbon may explain their wear resistance values comparable to those of plain carbon steels of equal hardness. At higher carbon content, the microstructure consists of martensite and retained austenite and the resistance to wear increases. When abraded by flint, the Cr-Mo steels exhibit a higher wear resistant than plain carbon steels. However, their resistance to wear by silicon carbide was constant and poorer than that of plain carbon steels.

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Table I

Chemical composition of the investigated steels

Standards DIN AISI	Chemical composition in wt. %															
Carbon steels	C	Si	Mn	P	S	Cu	Cr	Ni	Mo	Nb	Ti	V	W	Al	Co	Sn
C15 1015	0,20	0,23	0,56	0,013	0,018		0,013	0,02	0,007							
Ck22 (1020)	0,22	0,16	0,51	0,010	0,026	0,22	0,131	0,13	0,033					0,041	0,016	
Ck35 (1035)	0,36	0,22	0,63	0,011	0,014	0,05	0,104	0,05	0,011			0,003		0,018	0,013	
C45 1045	0,44	0,26	0,57	0,014	0,024	0,13	0,18	0,07	0,03					0,029		0,012
Ck53	0,55	0,29	0,68	0,017	0,027	0,20	0,14	0,07	0,04					0,032		0,013
C60 1060	0,60	0,31	0,76	0,010	0,031	0,20	0,13	0,09	0,03					0,003		0,013
Chromium steels																
28Cr4	0,27	0,12	0,79	0,010	0,030	0,11	0,94	0,15	0,045	0,001		0,002	0,009	0,029	0,022	
34Cr4 5132	0,31	0,30	0,80	0,024	0,029	0,09	0,98	0,07	0,018	0,001		0,002		0,052	0,010	
41Cr4 5140	0,42	0,30	0,60	0,015	0,030	0,20	0,98	0,12	0,03					0,044		0,013
Chromium-Molybdenum steel																
16CrMo4	0,22	0,23	0,79	0,009	0,031	0,10	1,17	0,12	0,224	0,002	0,002	0,002	0,005	0,034	0,015	
25CrMo4	0,26	0,24	0,71	0,016	0,034	0,22	1,05	0,12	0,191	0,001	0,002	0,002	0,006	0,027	0,016	
34CrMo4 4137	0,34	0,19	0,68	0,014	0,025	0,15	1,06	0,22	0,200	0,002	0,003	0,002	0,005	0,032	0,016	
42CrMo4 4140	0,45	0,29	0,65	0,012	0,035	0,16	1,15	0,10	0,228	0,002				0,039	0,012	
50CrMo4	0,53	0,26	0,62	0,013	0,026	0,12	0,96	0,07	0,193	0,003	0,003		0,004	0,032	0,013	

Table II

Heat treatments, hardness and microstructures of "as-received" steels

Designation	Heat treatment	Hardness HV10	Microstructures
C15 (1015)	normalizing	137±1	Ferrite, pearlite
Ck22 (1020)	normalizing	161±1	Ferrite, pearlite
Ck35 (1035)	normalizing	179±3	Ferrite, pearlite
Ck45 1045	normalizing	202±7	Ferrite, pearlite
Ck53	normalizing	225±6	Ferrite, pearlite
C60 (1060)	normalizing	242±4	Pearlite, with ferrite
28Cr4	normalizing	189±1	Ferrite, pearlite
34Cr4 (5132)	normalizing	208±3	Ferrite, pearlite
41Cr4 (5140)	normalizing	251±1	Pearlite, with ferrite
34CrMo4 (4137)	unknown	280±6	Ferrite, pearlite, bainite
42CrMo4 (4140)	unknown	311±10	Pearlite, martensite
50CrMo4	unknown	316±4	Ferrite, pearlite, bainite, martensite

Table III

Detailed heat-treatments, hardness and microstructures of steels hardened and tempered at 550°C

Designation	Hardening	Hardness HV10	Microstructures
Ck22 (1020)	820°C 15 min water	247±15	tempered martensite
Ck35 (1035)		304±8	
C45 (1045)		295±3	
Ck53		320±1	
C60 (1060)		347±4	
28Cr4	840°C 15 min water	304±6	tempered martensite
34Cr4 (5132)		318±7	
41Cr4 (5140)		337±6	
16CrMo4	900°C, 15 min, oil	322±5	Bainite
25CrMo4	880°C, 15 min, oil	317±3	Bainite
34CrMo4 (4137)	840°C, 15 min, warm bath	355±7	Tempered martensite
42CrMo4 (4140)	840°C, 15 min, warm bath	381±10	Tempered martensite
50CrMo4	840°C 15 min, warm bath	388±7	Tempered martensite

Note: All these samples were tempered at 550°C for 60 min in a warm bath.

Table IV

Detailed heat-treatments, hardness and microstructures of steels hardened and tempered between 170°C and 200°C

Designation	Hardening	Tempering	Hardness HV10	Microstructures
Ck22 (1020)	820°C 15 min water	180°C 60 min warm bath	503±10	Martensite, retained austenite
Ck35 (1035)			595±10	
C45 (1045)			627±7	
Ck53			676±2	
C60 (1060)			711±11	
28Cr4	840°C 15 min warm bath	180°C 60 min warm bath	497±9	Martensite, retained austenite
34Cr4 (5132)			536±16	
41Cr4 (5140)			620±9	
16CrMo4	900°C, 15 min, oil	180°C, 90 min, warm bath	474±1	Bainite, martensite
25MrMo4	880°C, 15 min, oil	180°C, 90 min, warm bath	498±5	Bainite, martensite
34CrMo4 (4137)	840°C, 15 min, warm bath	180°C, 60 min, warm bath	563±14	Martensite, retained austenite
42CrMo4 (4140)	840°C, 15 min, warm bath	180°C, 60 min, warm bath	632±10	
50CrMo4	840°C, 15 min, warm bath	180°C, 60 min, warm bath	680±9	

Table V

Results of the calculation of regression equations for carbon steels

Heat treatment	Dependent variable, x	Flint	SiC
Normalized	HV10	m = 0,1660 b = -9,80 corr.: 0,94	m = 0,0153 b = -0,094 corr.: 0,99
	w% C	m = 38,83 b = 6,59 corr.: 0,92	m = 3,02 b = 1,71 corr.: 0,98
Hardened and tempered at 550°C	HV10	m = 0,1461 b = -22,99 corr.: 0,85	m = 0,0047 b = 1,875 corr.: 0,98
	w% C	m = 37,92 b = 4,81 corr.: 0,92	m = 1,1484 b = 2,806 corr.: 0,95
Hardened and tempered at 180°C	HV10	m = 0,7798 b = -349,7 corr.: 0,99	m = 0,1028 b = -38,43 corr.: 0,99
	w% C	m = 409,9 b = -41,88 corr.: 0,99	m = 54,0 b = 2,15 corr.: 0,99

Regression equation: $W^{-1} = mx + b$

Table VI

Wear resistance values of alloy steels abraded by flint

Alloys	Cr/c	"As-received"			Hardened and tempered at 550°C			Hardened and tempered at 180°C		
		HV10	Wear resistance values [g^{-1}]	Relative wear resistance	HV10	Wear resistance values [g^{-1}]	Relative wear resistance	HV10	Wear resistance values [g^{-1}]	Relative wear resistance
28Cr4	0,80	189±1	27,1±4,2	1,25	304±6	38,5±4,4	1,80	497±9	313±62	8,29
34Cr4	0,73	208±3	23,1±2,0	0,94	318±7	30,7±2,1	1,31	536±16	284±25	4,16
41Cr4	0,54	251±1	25,9±4,3	0,81	337±6	22,4±2,3	0,85	620±9	211±40	1,58
16CrMo4	1,26	—	—	—	322±5	15,0±2,0	0,62	474±1	35,1±4,3	1,76
25CrMo4	0,93	—	—	—	317±3	16,3±1,1	0,70	498±5	33,1±3,4	0,86
34CrMo4	0,72	280±6	17,7±2,0	0,48	355±7	25,2±5,4	0,87	563±14	311±29	3,49
42CrMo4	0,59	311±10	25,9±1,9	0,62	381±10	33,8±5,1	1,03	632±10	333±60	2,33
50CrMo4	0,42	316±4	24,6±7,0	0,58	388±7	48,8±6,2	1,45	680±9	239±102	1,33

Table VII

Wear resistance values of alloy steels abraded by silicon carbide

Alloys	Cr/c	"As-received"			Hardened and tempered at 550°C			Hardened and tempered at 180°C		
		HV10	Wear resistance values [g^{-1}]	Relative wear resistance	HV10	Wear resistance values [g^{-1}]	Relative wear resistance	HV10	Wear resistance values [g^{-1}]	Relative wear resistance
28Cr4	0,80	189±1	2,69±0,20	0,96	304±6	6,32±0,12	1,91	497±9	22.6±1,4	1,79
34Cr4	0,73	208±3	3,17±0,15	1,03	318±7	5,74±0,22	1,70	536±16	21,2±1,3	1,27
41Cr4	0,54	251±1	4,70±0,49	1,25	337±6	4,13±0,09	1,19	620±9	22,1±1,3	0,87
16CrMo4	1,26				322±5	2,01±0,18	0,59	474±1	10,2±0,6	0,99
25CrMo4	0,93				317±3	2,76±0,14	0,82	498±5	10,4±1,0	0,81
34CrMo4	0,72	280±6	2,40±0,22	0,57	355±7	3,73±0,71	1,05	563±14	18,5±0,9	0,95
42CrMo4	0,59	311±10	4,23±0,54	0,91	381±10	4,82±0,37	1,32	632±10	17,8±1,1	0,67
50CrMo4	0,42	316±4	3,32±0,28	0,70	388±7	5,76±0,42	1,56	680±9	19,2±1,5	0,61

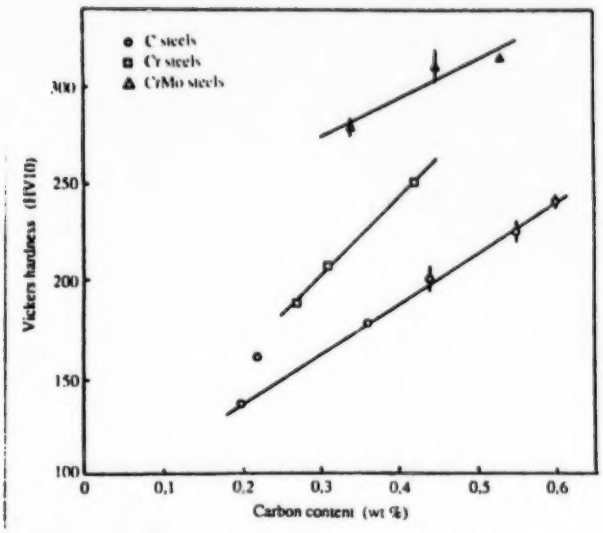


Fig. 1 Relation between hardness and carbon content of the steels in the "as-received" condition.

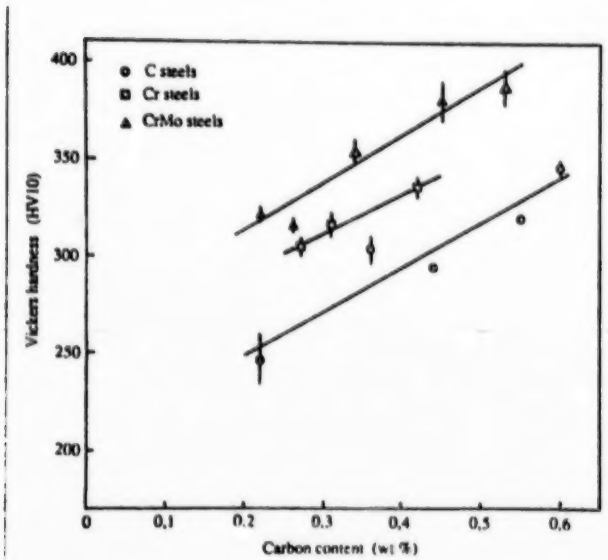


Fig. 2 Relation between hardness and carbon content of the steels hardened and tempered at 550°C.

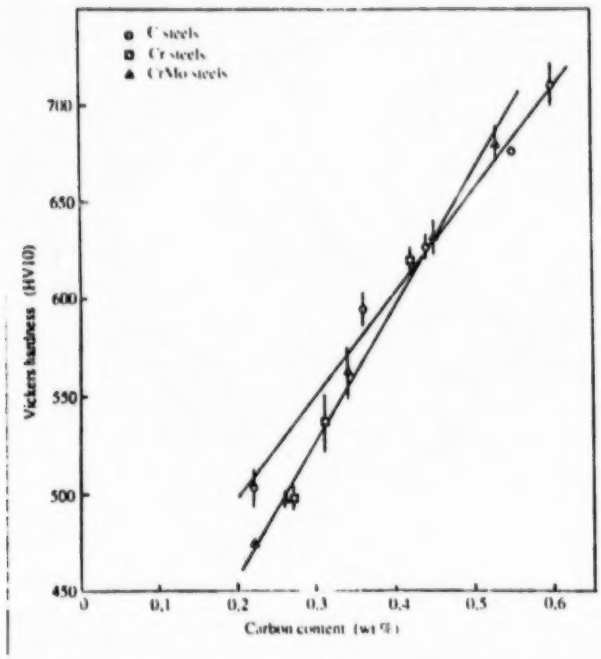


Fig. 3 Relation between hardness and carbon content of the steels hardened and tempered between at 180°C.

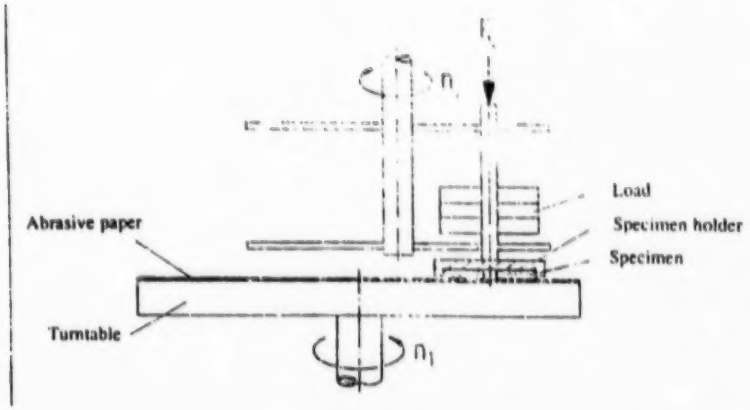


Fig. 4 Schematic of the wear test rig.

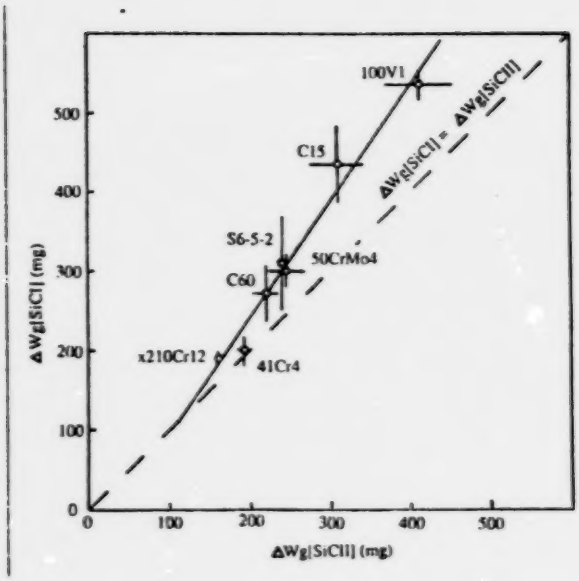
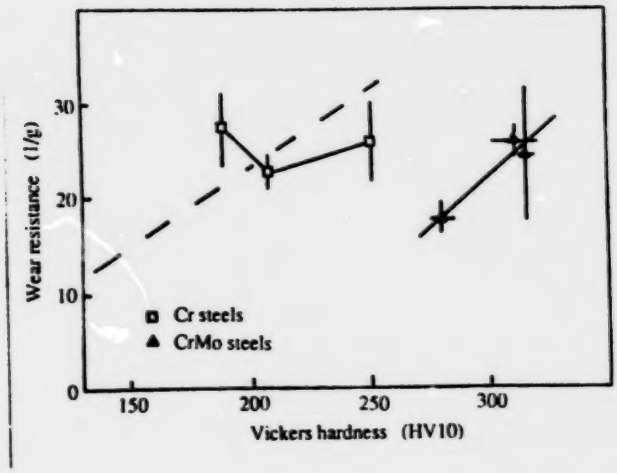


Fig. 5 Comparison between the weight loss produced by two different batches of silicon carbide abrasive papers of the same nominal denomination (220 grit).



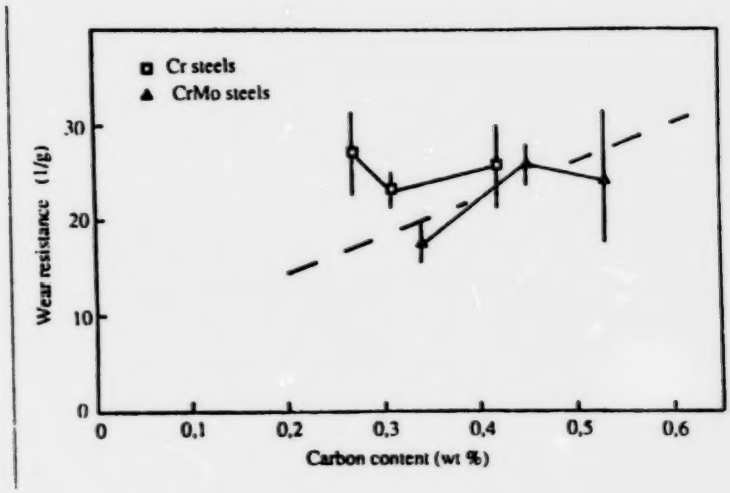
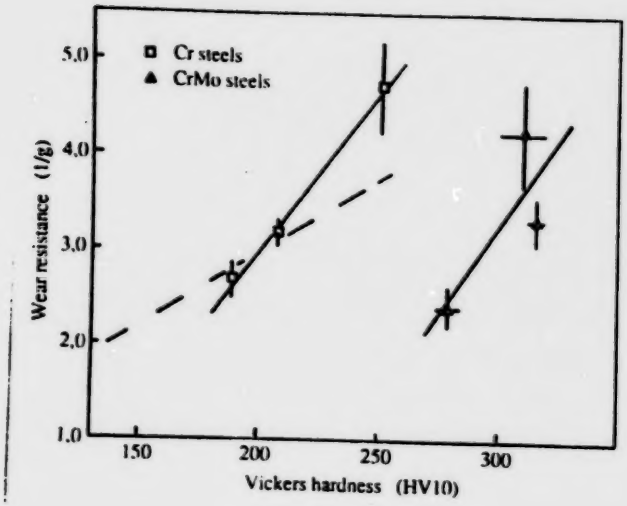


Fig. 6 Resistance to wear by flint of the normalized alloy steels plotted against a) the bulk hardness, b) the carbon content.



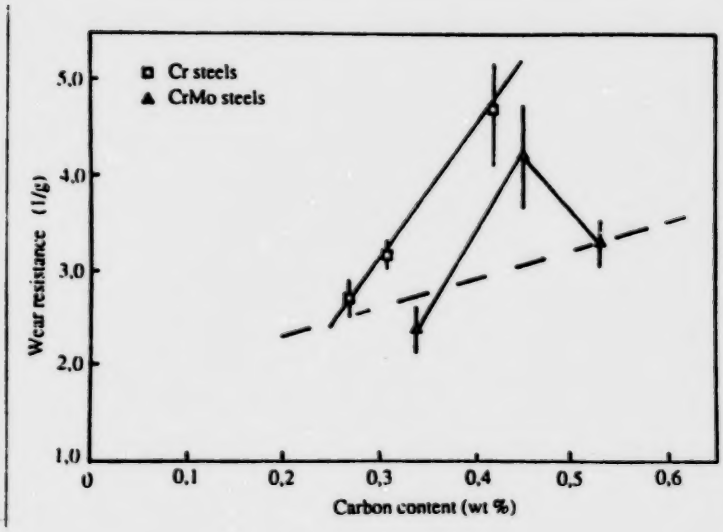
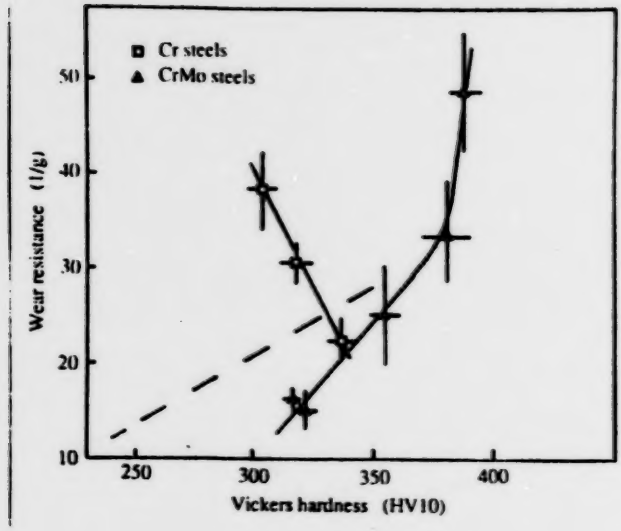


Fig. 7 Resistance to wear by SiC of the normalized alloy steels plotted against a) the bulk hardness, b) the carbon content.



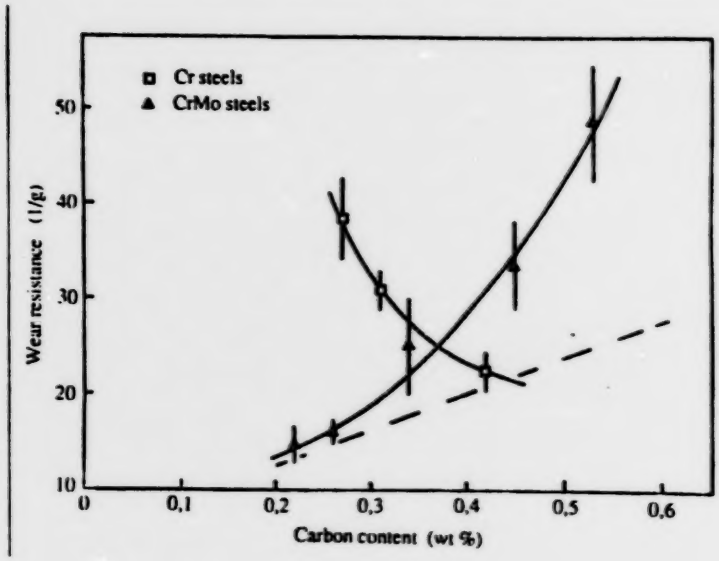
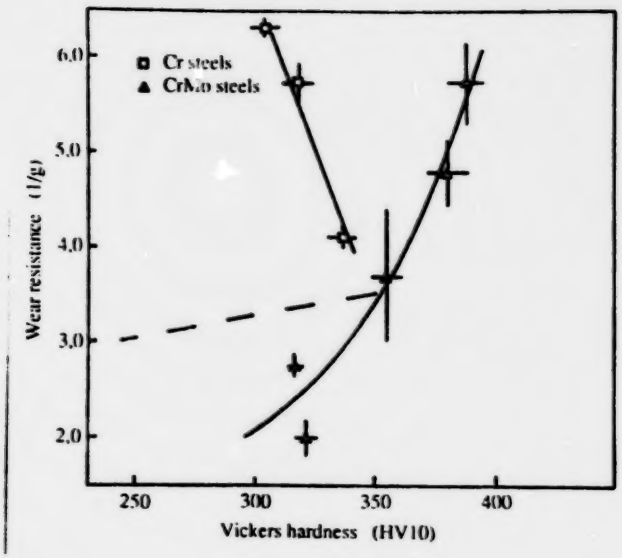


Fig. 8 Resistance to wear by flint of the alloys steels hardened and tempered at 550°C plotted against a) the bulk hardness, b) the carbon content.



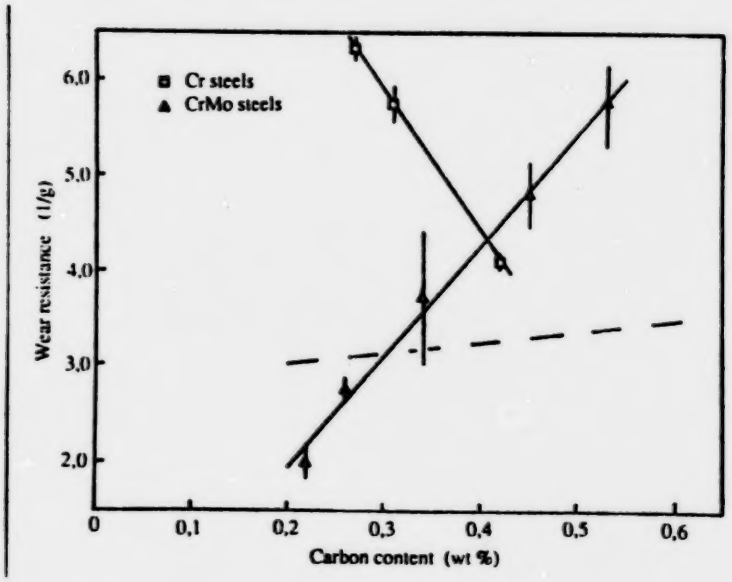


Fig. 9 Resistance to wear by SiC of the alloy steels hardened and tempered at 550°C plotted against a) the bulk hardness, b) the carbon content.

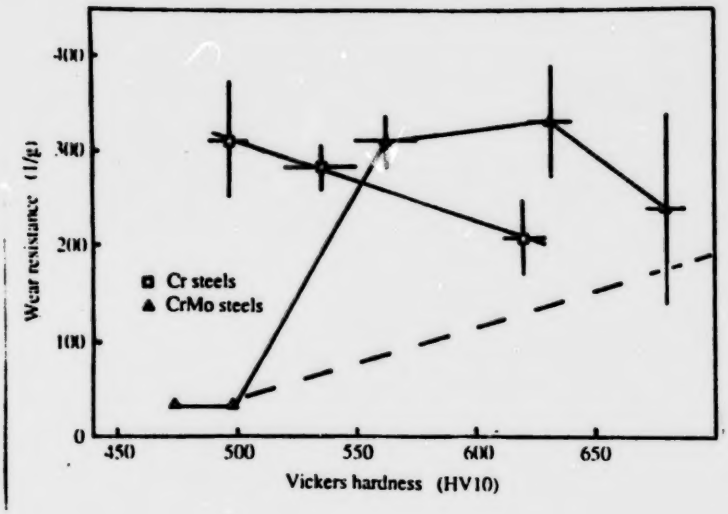


Fig. 10 Resistance to wear by flint of the alloy steels hardened and tempered at 180°C plotted against the bulk hardness.

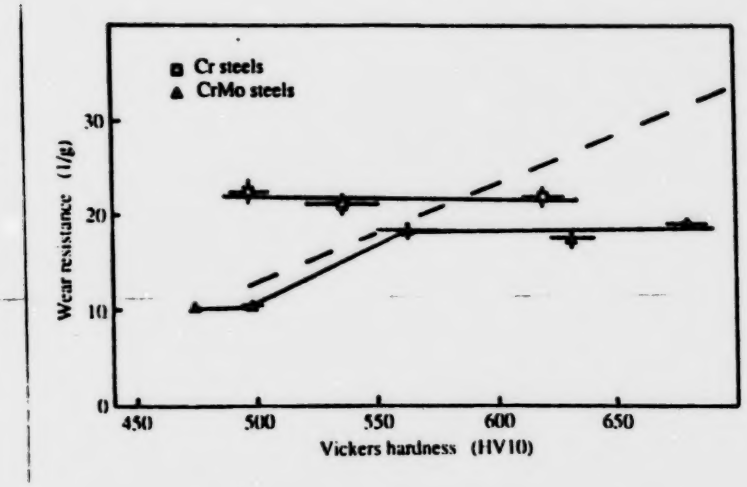


Fig. 11 Resistance to wear by SiC of the alloy steels hardened and tempered at 180°C plotted against the bulk hardness.

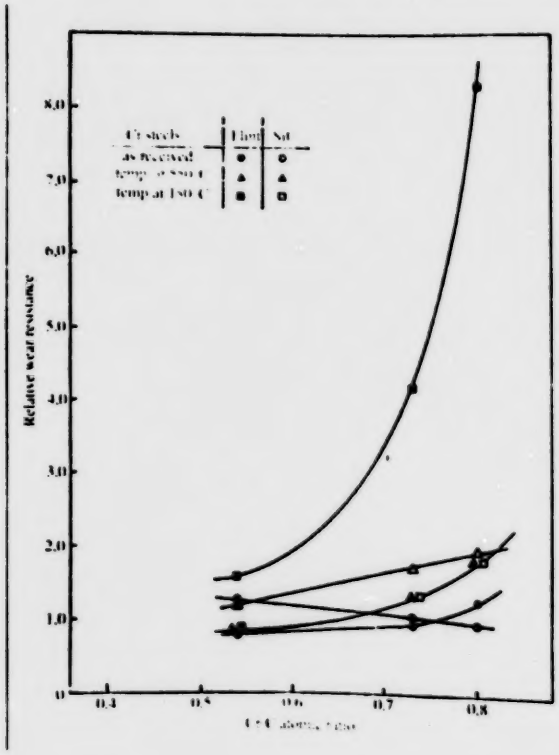


Fig. 12 Relative wear resistance of the chromium steels plotted against the chromium-to-carbon atomic ratio.